Electromagnetic waves with frequencies near the local proton gyrofrequency: ISEE-3 1 AU observations

Bruce T. Tsurutani, John K. Arballo, John Mok, and Edward J. Smith
Jet Propulsion Laboratory, California Institute of Technology, Pasadena

Glenn M. Mason and Lun C. Tan
Department of Physics and Astronomy, College Park, Maryland

Abstract. Low Frequency (LF) electromagnetic waves with periods near the local proton gyrofrequency have been detected in interplanetary space by the magnetometer onboard ISEE-3. Transverse peak-to-peak amplitudes as large as $\Delta\vec{B}/|B| \sim 0.4$ have been noted with compressional components ($\Delta|B|/|B|$) typically ≤ 0.1. Generally, the waves have even smaller amplitudes, or are not detectable within the solar wind turbulence. The waves are elliptically/linearly polarized and are often, but not always, found to propagate nearly along $\vec{B}_0$. Both right- and left-hand polarizations in the spacecraft-frame have been detected. The waves are observed during all orientations of the interplanetary magnetic field, with the Parker spiral orientation being the most common case. Because the waves are detected at and near the local proton cyclotron frequency, the generation mechanism must almost certainly be solar wind pickup of freshly created hydrogen ions. Possible sources for the hydrogen are the Earth's atmosphere, coronal mass ejections from the Sun, comets and interstellar neutral atoms. At this time it is not obvious which potential source is the correct one. Statistical tests employing over one year of ISEE-3 data will be done in the near future to eliminate/confirm some of these possibilities.

Introduction

The interplanetary magnetic field at 1 AU is typically quite featureless [Siscoe et al., 1968; Bavassano et al., 1982; Tu et al., 1984; Tsurutani et al., 1990]. It is characterized by a relatively smooth power law spectrum with a frequency dependence of $\sim f^{-5/3}$. Although long period (10 min to hours) Alfvén waves are an ever-present feature of the solar wind [Coleman, 1967; Belcher and Davis, 1971], the corresponding spectra do not have characteristic peak intensities indicative of any wave generation by resonant instabilities.

The purpose of this paper is to describe, for the first time, medium amplitude waves with periods near the local proton gyrofrequency detected at 1 AU. The International-Sun-Earth-Explorer-3 (ISEE-3) magnetometer data was used in the survey. ISEE-3 orbited the L_1 libration point, some $\sim 240\ R_E$ upstream of the Earth [Farquhar et al., 1977]. The detection of waves at the proton gyrofrequency, in the spacecraft frame, indicates that these waves are generated by the pickup of hydrogen atoms which have initial velocities small relative to the spacecraft. This situation is quite similar to the pickup of cometary H_2O group ions and the generation of waves at the H_2O group ion cyclotron frequency [Tsurutani and Smith, 1986].

Approach

High time resolution (6 vectors s^{-1}) ISEE-3 magnetic field data [Frandsen cl al., 1978] were used in a survey to search for 1 .ow Frequency waves at 1 AU. Seventeen intervals were selected from our study. The se are listed in "1'able 1. Fourteen of the intervals have 6-24 hours duration each, Because these intervals are associated with energetic solar flare particle events, five more one hour intervals arc included in the study. These latter events rrrc not associated with energetic particle events.

Results

LF waves were detected in most of the seventeen intervals selected (See '1'able 1). The waves arc usually of small amplitude, arc sporadic in occurrence, and therefore may have been missed in previous surveys of 1 AU interplanetary magnetic field data. An example of waves in one interval is shown in Figure 1. This example was selected because the waves had unusually large amplitudes and thus were particularly easy to identify. These transverse waves have a peak-k-peak transverse amplitude of - 7 nT in a ~ 18 nT field or $\Delta\vec{B}/|B|$ -- 0.3. The compressional component, A| B| / |B|, is less than 0.05. The wave period varies from 4 to 6s. The local proton cyclotron period is 3.6s, thus the waves have periods slightly lower than the local proton gyroperiod ('l'p). Note that the interplanetary magnetic. field (GSE coordinates) components arc B_x ~ -11 nT and B_y - 11 n']'. This is a positive (outward) Parker spiral field direction. B_z - -8 nT.

Wc usc the Principal Axis Analysis method (Sonnerup and Cahill, 1967) to identify the direction of maximum, intermediate and minimum variances, standardly labeled as $\hat{B}_1$, $\hat{B}_2$ and $\hat{B}_3$, respectively. The minimum variance direction is the wave propagation ($\hat{k}$) direction for planar electromagnetic waves (Smith and Tsurutani, 1976). The most accurate method of wave analysis is to examine one cycle at a time (Tsurutani et al., 1993). Analyzing several or more cycles at the same time gives an "average" result, at best. Variations in degree of polarization (circular to linear) and variations in directions of propagation have been noted in a single wave packet. "Averaging over several cycles" can also lead to substantial errors if there arc changes in the IMF direction during the interval [Tsurutani et al., 1993], or if the waves arc nonlinear [Tsurutani, 1992]. wc have therefore only analyzed single cycles at a time within this paper.

Figure 2 gives the hodogram for onc cycle. of the wave packet in Figure 1 in Principal Axis Coordinates. The lime interval of analysis is 0438:08100438:14 UT. The beginning of the interval is indicated by a "D" and the end of the interval with an "ii". The ambient magnetic field is out of the paper. The hodogram shows that there is a uicc 360° cycle to the wave (analyses of other wave intervals gave similar results). The wave is left-haml elliptically polarized (λ_1/λ_2 = 30.6), propagating at an angle of 59° relative to the ambient magnetic field.

Figure 3 gives the power spectrum of lhc waves from 0416 - 0439 UT day 158, 1979, the same general interval of time as in Figures 1 and 2. A fic.lcl-aligned coordinate system is used, with $\hat{B}_1$, along the average field direction, B_2 in the $\hat{\Omega}_n \times \hat{B}_1$

direction (where $\hat{\Omega}_n$ is the direction of the north ecliptic pole), and $\hat{B}_3$ completing the right-hand system. The power spectra for |B| and the lwo transverse components, B_2 and B_3, arc plotted. A broad increase in wave power can be noted near f ~ 2 x 10"1 Hz, the local proton cyclotron frequency (denoted by f_p). The power is - 3-5 $nT^2\,Hz^{-1}$ in the transverse components and 5 x 1 $0^{-1}\,nT^2\,Hz^{-1}$ in the compressional component. The power in the wave compressional component is about an order of magnitude lower than in the transverse components. '1'hose spectra arc unlike what is typically seen in the solar wind.

Figure 4 is an example of the waves detected in an interval where solar flare. particles arc not present. The event is from 0033-003511'1' May 8, 1981. 'J'here. are. six cycles of a wave packet present between 0033:30 and 0034:20 UT. The wave period is - 8.5s. The waves arc a mixture of right- anti left-hand Polari?.alien and propagate at angles between 3° and 19° relative to the ambient magnetic field. The waves arc highly elliptically polarized in each cycle (λ_1/λ_2 ranges between 3.3 and 40.5). The local ion proton cyclotron frequency is - 9.9s, so these waves have frequencies slightly higher than the local Ω_p.

Table 2 gives the results of Principal Axis Analysis of a number of wave cycles from Figures 1 and 2 and three other intervals as well. From the Table, we find that the wave periods arc close to the proton cyclotron period and they arc often, but not always, found to propagate nearly along $\vec{B}_o$. The waves are typically highly elliptically to linearly polarized. A mixture of right-hand and left-hand polarizations have been detected. When a sense of rotation can be found, the typical sense is left-handed in the spacecraft frame.

Sixteen short 4-minute intervals where waves were prc.sent wereselectedat random. Figure 5 displays the GSE-B_x and -B_y components of tile average field for these intervals. Most of the intervals lie along the Parker spiral direction (this is the most probable direction of the field, so there is nothing unusual shout this orientation). '1'here is no tendency of the field to be in the radial direction.

Discussion

Comparison to the Ulysses Results

The waves discussed in this paper have many properties that are similar to those detected by Ulysses at 5 AU [Smith et al., 1993]. The waves detected at 5 AU arc believed to be due to the pick up of interstellar neutrals. The waves in this study have medium amplitude ($\Delta B/|B|$ - 0.4) transverse components (the Ulysses waves arc slightly larger), and have frequencies near the local proton cyclotron frequency. Both the 1 and 5 AU waves arc a mixture of left-hand and right-hand polarizations, with left-hand waves more prominent. The waves discussed in this paper arc elliptically to linearly polarized. The genera] polarization of the 5 AU waves was not reported [Smith et al., 1993], but the onc example shown was circularly polarized propagating along the magnetic field (θ_{kB} = 5°).

The onc major difference of the waves at 1 AU is that they are detected during all field orientations, with the Parker spiral orientation the most likely. The 5 AU waves arc detected when the field is radial. In either case, the pickup ions would generate right-hand waves propagating toward the Sun through the resonant ion beam instability. Because the solar wind speed is larger than the wave phase speed, these waves would be convected in the antisolar direction aod would be detected as left-had polarized (at the proton cyclotron frequency in the spacecraft frame).

Possible Sources of the ISEE-3 Waves

The detection of electromagnetic waves at the proton cyclotron frequency at the ISEE-3 orbit about the L_1 libration is a big surprise and also a mystery at this time. Although the waves reported here have similarities to those detected at 5 AU, interstellar hydrogen is not expected to get so close to the Sun. 'J'here is onl y a 0.1 probability of penetration to a distance of - 1.1 AU from the Sun [Holzer, 1977]. The density of neutrals should be considerably below that at 5 AU. Recent calculations [R. Illing and E. Hildner, personal communication, 1993] have indicated that substantial neutrals associated with coronal mass ejections (CME) could escape into interplanetary space. The fraction of atoms that remain as neutrals depends on the velocity of the CME ((he higher the velocity, the higher the fraction), and on the amount of self-shielding present. These CME neutrals would have high velocities. Unless there is some mechanism to slow them down, waves generate after their ionization would be strongly Doppler shifted away from the proton cyclotron frequency. Another potential source of neutrals is the Earth's atmosphere. Holzer estimated a number density of -1 .S x 10^{-3} cm^{-3} at 0.01 AU, but recent (preliminary) Galileo measurements made at lunar distances (~ 60 R_e) have increased this estimated value substantially [C. Hord, personal communication, 1 993].

The difficulty with any of these potential sources is obtaining a sufficient ion beam density. In space plasmas, the ion beam densities for' wave generation have been found to be roughly 0.1 to 1 .0% of the ambient (solar wind) density. This would require beam densities of 5 x 10^{-3} to 5 x 10”^{2} ions cm^{-3}. This value taken with the photoionization/charge exchange time scale of - 106s at 1 AU, make the neutral number density somewhat difficult to attain by any of the above sources.

Another possibility is generation by instabilities assoc. iated with unusual ion or electron distributions within the solar wind, Proton beam instabilities are possible, but the waves would be generated near the cyclotron frequency in the rest frame of the resonant particles, Since the ratio of the ion cyclotron wave phase velocity (- VA) to the. solar wind speed is - 1/7, these waves would be Doppler shifted to - $7\Omega_p$ in lhe spacecraft frame.

Resonant interactions with relativistic - 1 MeV electrons (these energies are necessary for resonance with the.se frequency waves) propagating from the Sun is a generation mechanism that can be easily ruled out. Some of the wave events were detected when relativistic electrons were clearly absent. Also, because solar flare electron events typically have broad power-law type velocity distributions and are not monoenergetic in nature, it would be extremely difficult to explain the limited frequency range of the waves. Resonance with solar flare proton beams would generate right-hand polarized waves propagating in the solar wiad direction. These waves would be detected as right-handed in the spacecraft frame, at odds with present observations.

The broad power-law spectrum of solar' flare protons would again rule out relatively well-de.fineel peak frequencies.

Final Comments

Pickup of cold hydrogen neutrals in the most likely source of the waves. To test some of the various possibilities, wc will examine the first year of ISEE-3 data to a) determine if there is a wave amplitude and occurrence frequency dependence on radial distance (just after the spacecraft was launched and went from the Earth to 240 R_e upstream), b) determine if there is a correlation between wave occurrence and CME events, and c) determine if there is an annual variation in wave occurrence. ***Study*** a) will establish if the Earth is the source, and b) if CMEs are the cause. Since interstellar neutrals enter the heliosphere from a well - define.d direction, there is substantial focussing in a region on the backside of the sun. '1'bus, if the neutrals arc from interstellar space, there may be greater wave intensity in the region where the neutrals arc gravitationall y focussed (test c). A preliminary cut of this data set has not revealed au obvious answer. Further analyses Will be necessary.

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ELECTROMAGNETIC WAVES FREQUENCIES PROTON

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Table 1. intervals anal yzed for the presence of waves. The top twelve intervals correspond to intervals where solar energetic ions were present. The bottom five intervals arc free of solar flare particles. The presence/lack of presence waves arc noted by a Y (yes) or N (no). An approximate maxi mum peak-to-peak transverse wave amplitude is indicated.

Table 2. 1,1; wave properties. The columns correspond to the date, time (UT), wave period, local proton gyroperiod, wave propagation direction relative to the ambient magnetic field, PAA eigenvalue ratios, and sense of polarization.

Figure 1. LF waves with periods near the local proton gyrofrequency.

Figure 2. A hodogram for one wave cycle of the event shows in Figure 1.

Figure 3. Power spectra of the magnetic. field for an interval containing the event in Figure 1. The local proton gyrofrequency (f_p) is denoted. B_2 and B_3 correspond to power transverse to the average field direction.

Figure 4. Same as Figure 1, but for a time period when solar flare energetic particles arc not present.

Figure 5. The IMF orientation for sixteen wave events selected at random,

TABLE 1

INTERVAL	DATE	DAY	START TIME	STOP TIME		WAVES	P-P AMPLITUDE
1	SEP 23, 1978	266	0800	1900		Y	3 nT
2	SEP 25, 1978	268	0600	1300		Y	3 nT
3	JUN 06, 1.979	157	1100	1700		N?	
4	JUN 07, 1979	158	0000	0600		Y	1.5 nT
5	AUG 1.9, 1979	231	1400	2000		Y	1.5 nT
6	AUG 20, 1979	232	1200	1800		N?	.
7	SEP 14, 1979	257	0800	0200	(258)	Y	3 nT
8	SEP 17, 1979	260	1100	1900		Y	2 nT
9	APR 24, 1981	114	1200	1832		Y	4 nT
10	APR 25, 1981	115	1800	2400		Y	1 .5 nT
11	MAY 10,1981	130	0000	2400		Y	2 nT
12	MAY 16, 1981	136	0500	0500	(137)	Y	2 nT

Intervals Preceding Solar Cosmic Ray Events

INTERVAL	DATE	DAY	START TIME	STOP TIME	WAVES	P-P AMPLITUDE
1	SEP 22, 1978	265	0000	0100	Y	5 nT
2	JUN 05, 1979	156	0000	0100	Y	2 nT
3	AUG 18, 1979	230	0000	0100	Y	2 nT
4	APR 23, 1981	113	0000	0100	Y	1 nT
5	MAY 08, 1981	128	0000	0100	Y	2 nT

Table 1

ISEE-3 WAVES

DATE	TIME	Tw	T_p	θ_{kB}	λ_1/λ_2	λ_2/λ_3	Pol
9/23/78	1314:16-31	10.0s	12.5s	8°	12.2	4.1	l.h. ellip.
9/23/78	1314:42-46	4.0s	12.5s	24°	7.7	9.1	l.h. ellip.
6/07/79	417:30-38	4.5s	4.05	4°	5.5	6.8	linear
6/07/79	437:47-54	5.0s	3.6s	42°	14.0	5.0	r.h. ellip.
6/07/79	438:08-14	5.0s	3.6s	59°	30.6	1.8	l.h. ellip.
9/14/79	1041:37-50	7.5s	12.3s	68°	70.2	1.7	linear
9/14/79	1041:49-59	10.0s	12.3s	8°	7.5	43.4	r.h. circ/ellip.
9/14/79	1141:48-54	4.5s	12.2s	5°	9.8	1.9	l.h. ellip.
9/14/79	1141:43-03	6.5s	12.2 s	6“	4.0	7.3	l.h. ellip.

Table 2

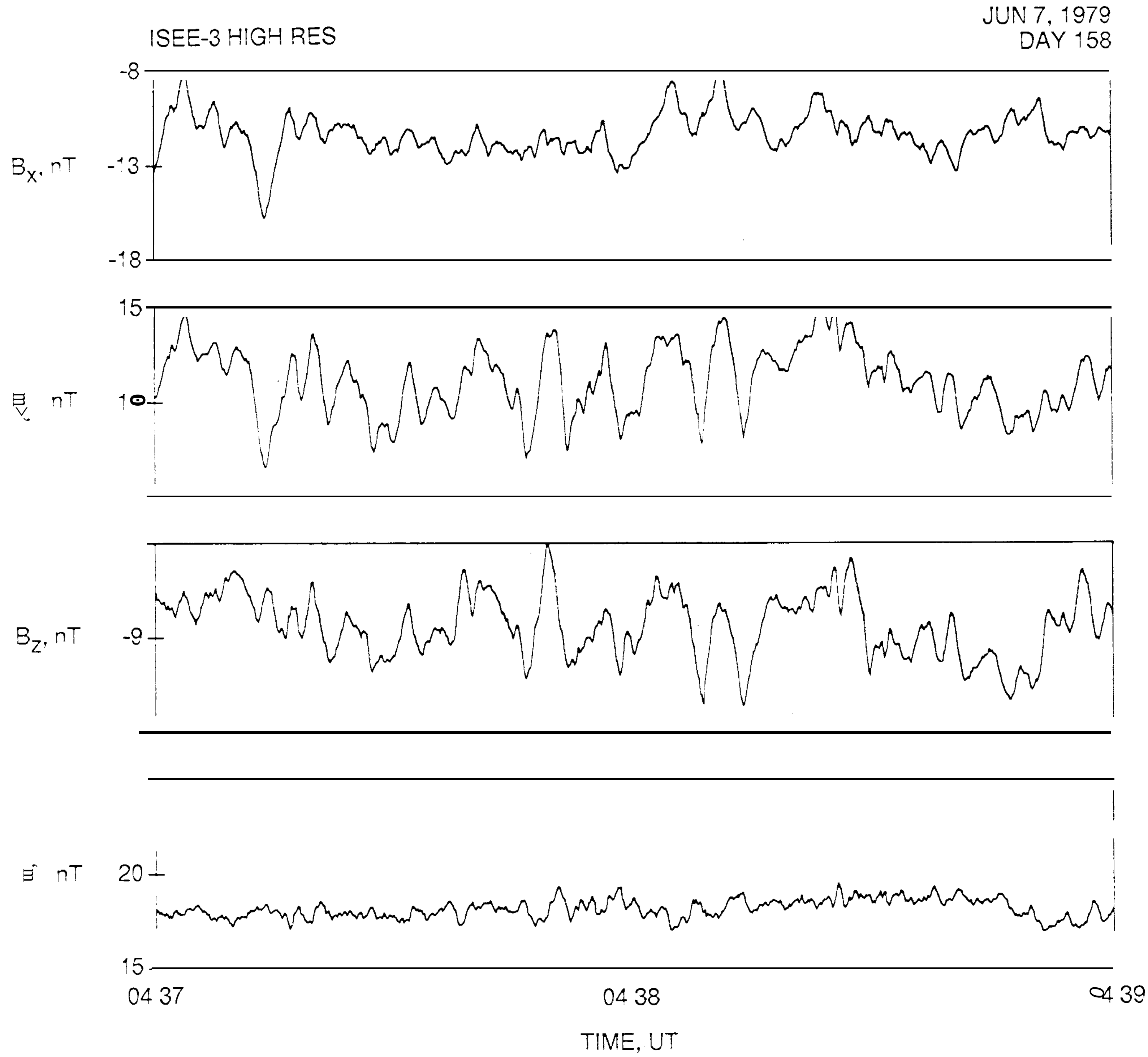
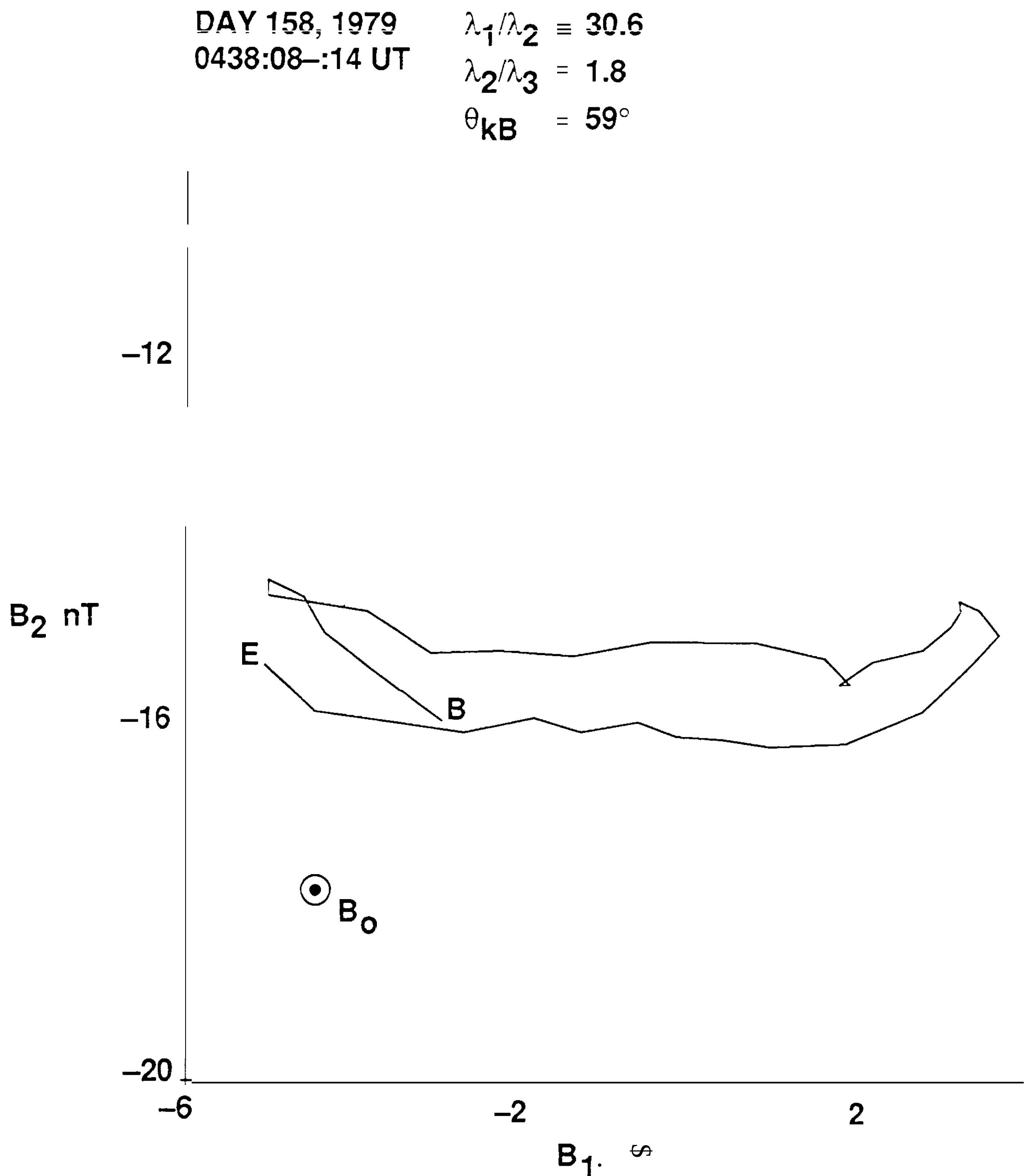
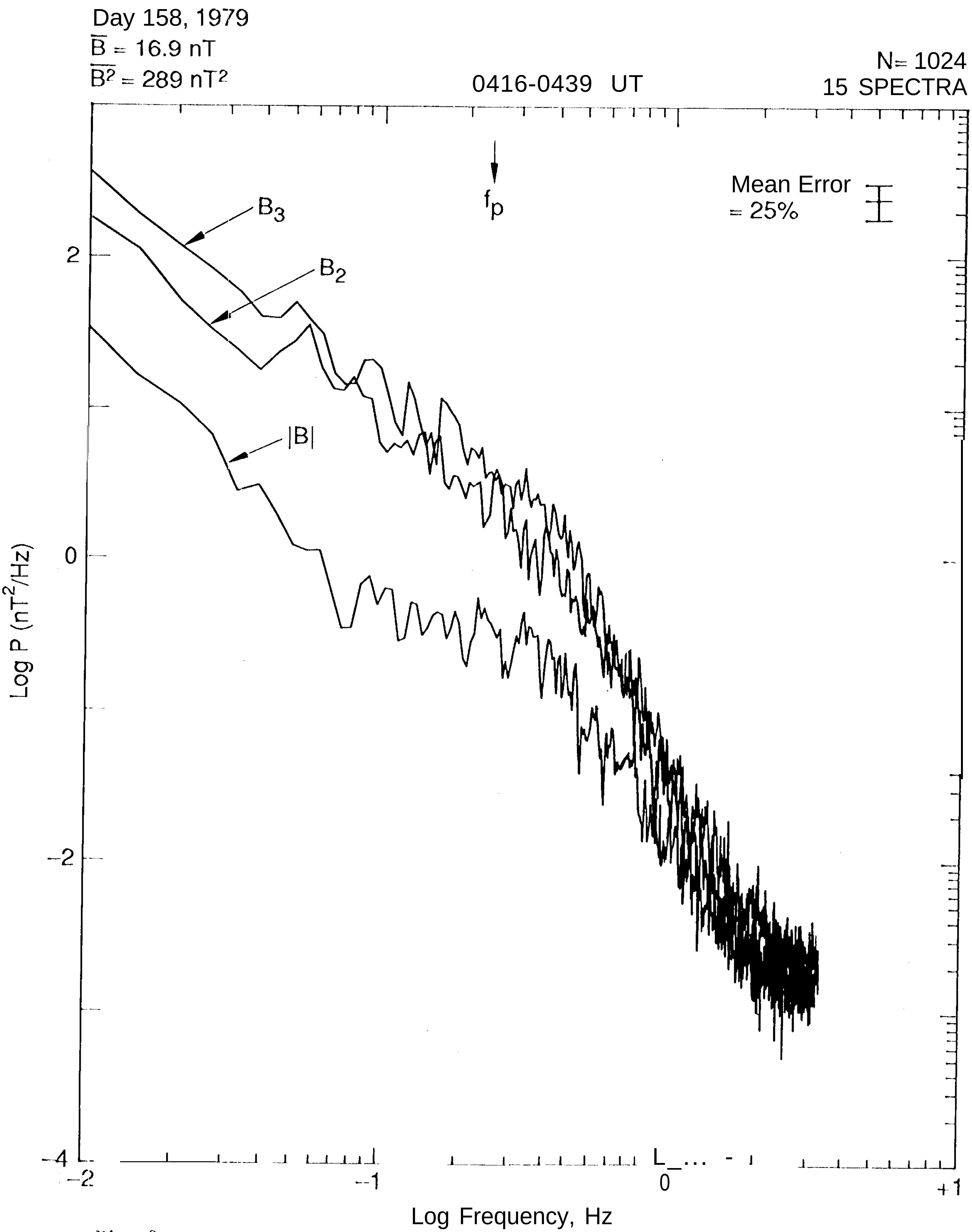

ISEE-3 HIGH RES
JUN 7, 1979
DAY 158
B_X, nT
-8
-13
-18
15
10
B_Z, nT
-9
nT
20
15
04 37
04 38
04 39
TIME, UT

Fig. 1



DAY 158, 1979
0438:08–:14 UT
$\lambda_1/\lambda_2 \equiv 30.6$
$\lambda_2/\lambda_3 = 1.8$
$\theta_{kB} = 59°$
B_2 nT
−12
−16
−20
−6
−2
2
B_1
E
B
B_o

Fig. 2



Day 158, 1979
$\overline{B} = 16.9$ nT
$\overline{B^2} = 289$ nT^2
0416-0439 UT
N= 1024
15 SPECTRA
f_p
Mean Error = 25%
B_3
B_2
|B|
2
0
-2
-4
Log P (nT^2/Hz)
-2
-1
0
+1
Log Frequency, Hz

Fig. 3

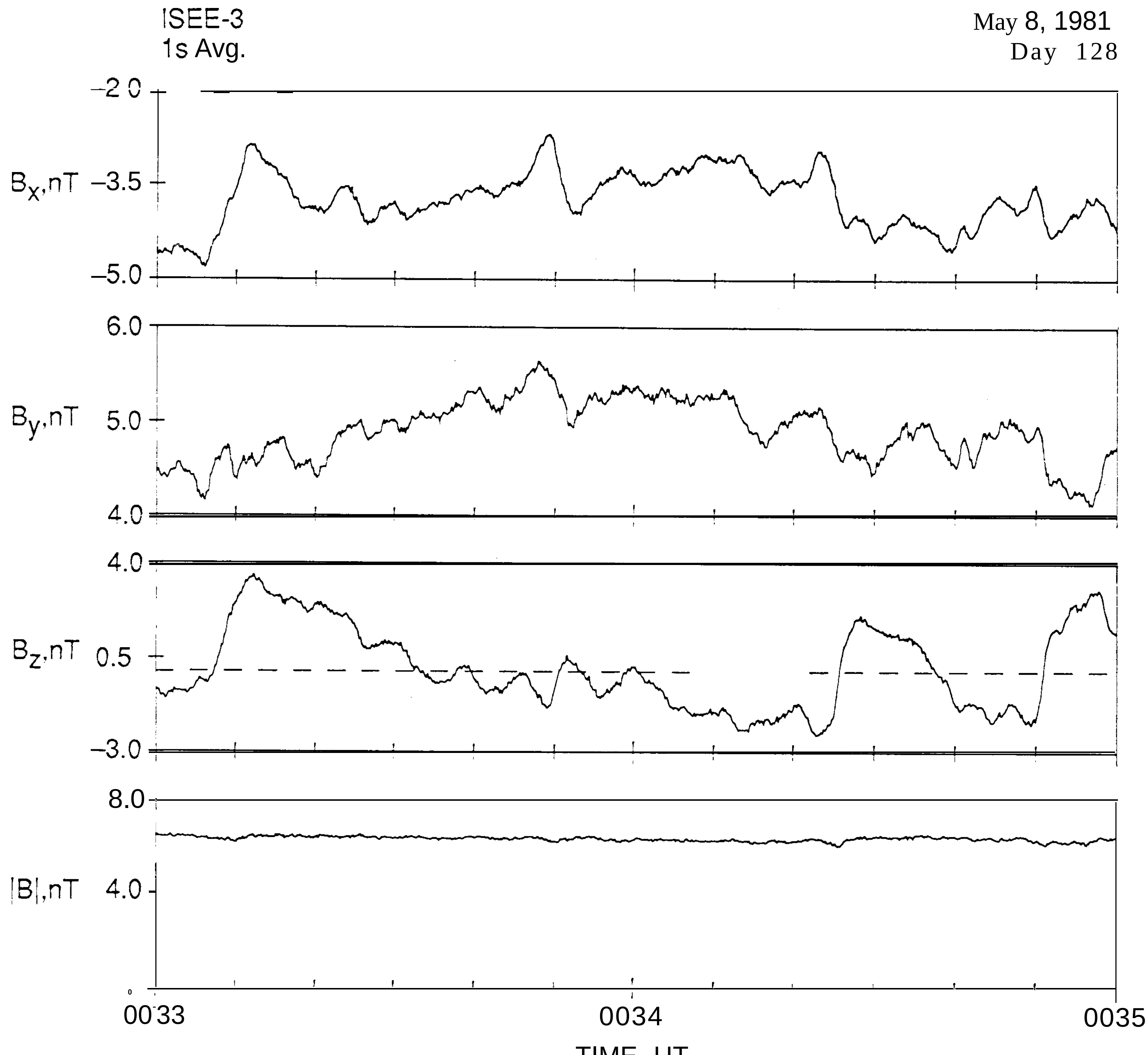

ISEE-3
1s Avg.
May 8, 1981
Day 128
B_x,nT
−2.0
−3.5
−5.0
B_y,nT
6.0
5.0
4.0
B_z,nT
4.0
0.5
−3.0
|B|,nT
8.0
4.0
0
0033
0034
0035
TIME, UT

Fig. 4